

DFTT 71/99
hep-ph/9912427

Neutrino oscillations and neutrinoless double- β decay

C. Giunti

*INFN, Sezione di Torino, and Dipartimento di Fisica Teorica, Università di Torino,
Via P. Giuria 1, I-10125 Torino, Italy*

Abstract

We consider the scheme with mixing of three neutrinos and a mass hierarchy. We show that, under the natural assumptions that massive neutrinos are Majorana particles and there are no unlikely fine-tuned cancellations among the contributions of the different neutrino masses, the results of solar neutrino experiments imply a lower bound for the effective Majorana mass in neutrinoless double- β decay. We also discuss briefly neutrinoless double- β decay in schemes with mixing of four neutrinos. We show that one of them is favored by the data.

Presented at TAUP'99, 6–10 September 1999, College de France, Paris, France.

Neutrino oscillations [1] have been observed in solar and atmospheric neutrino experiments. The corresponding neutrino mass-squared differences are

$$\Delta m_{\text{sun}}^2 \sim 10^{-6} - 10^{-4} \text{ eV}^2 \quad (\text{MSW}), \quad (0.1)$$

in the case of MSW transitions, or

$$\Delta m_{\text{sun}}^2 \sim 10^{-11} - 10^{-10} \text{ eV}^2 \quad (\text{VO}), \quad (0.2)$$

in the case of vacuum oscillations, and

$$\Delta m_{\text{atm}}^2 \sim 10^{-3} - 10^{-2} \text{ eV}^2. \quad (0.3)$$

These values of the neutrino mass-squared differences and the mixing required for the observed solar and atmospheric oscillations are compatible with the simplest and most natural scheme with three-neutrino mixing and a mass hierarchy:

$$\underbrace{m_1 \ll m_2 \ll m_3}_{\Delta m_{\text{atm}}^2} \quad (0.4)$$

This scheme is predicted by the see-saw mechanism [1], which predicts also that the three light massive neutrinos are Majorana particles. In this case neutrinoless double- β decay ($\beta\beta_{0\nu}$) is possible and its matrix element is proportional to the effective Majorana mass

$$|\langle m \rangle| = \left| \sum_k U_{ek}^2 m_k \right|, \quad (0.5)$$

where U is the neutrino mixing matrix and the sum is over the contributions of all the mass eigenstate neutrinos ν_k ($k = 1, 2, 3$).

In principle the effective Majorana mass (0.5) can be vanishingly small because of cancellations among the contributions of the different mass eigenstates. However, since the neutrino masses and the elements of the neutrino mixing matrix are independent quantities, if there is a hierarchy of neutrino masses such a cancellation would be the result of an unlikely fine-tuning, unless some unknown symmetry is at work. Here we consider the possibility that no such symmetry exist and *no unlikely fine-tuning operates to suppress the effective Majorana mass* (0.5) [2]. In this case we have

$$|\langle m \rangle| \simeq \max_k |\langle m \rangle|_k, \quad (0.6)$$

where $|\langle m \rangle|_k$ is the absolute value of the contribution of the massive neutrino ν_k to $|\langle m \rangle|$:

$$|\langle m \rangle|_k \equiv |U_{ek}|^2 m_k. \quad (0.7)$$

In the following we will estimate the value of $|\langle m \rangle|$ using the largest $|\langle m \rangle|_k$ obtained from the results of neutrino oscillation experiments.

Let us consider first $|\langle m \rangle|_3$, which, taking into account that in the three-neutrino scheme under consideration $m_3 \simeq \sqrt{\Delta m_{31}^2} = \sqrt{\Delta m_{\text{atm}}^2}$, is given by

$$|\langle m \rangle|_3 \simeq |U_{e3}|^2 \sqrt{\Delta m_{\text{atm}}^2}. \quad (0.8)$$

Since the results of the CHOOZ experiment [3] and the Super-Kamiokande atmospheric neutrino data [4] imply that $|U_{e3}|^2$ is small ($|U_{e3}|^2 \lesssim 5 \times 10^{-2}$ [5]), the contribution $|\langle m \rangle|_3$ to the effective Majorana mass in $\beta\beta_{0\nu}$ decay is very small [6,2,7]. The upper bounds for $|\langle m \rangle|_3$ as functions of Δm_{atm}^2 obtained from the present experimental data are shown in Fig. 1. The dash-dotted upper limit has been obtained using the 90% CL exclusion curve of the CHOOZ experiment (taking into account [1] that $|U_{e3}|^2 = \frac{1}{2} (1 - \sqrt{1 - \sin^2 2\vartheta_{\text{CHOOZ}}})$, where ϑ_{CHOOZ} is the two-neutrino mixing angle measured in the CHOOZ experiment), the dashed upper bound has been obtained using the results presented in Ref. [5] of the analysis of Super-Kamiokande atmospheric neutrino data (at 90% CL) and the solid upper limit, that surrounds the shadowed allowed region, has been obtained using the results presented in Ref. [5] of the combined analysis of the CHOOZ and Super-Kamiokande data (at 90% CL). The dotted line in Fig. 1 represents the unitarity limit $|\langle m \rangle|_3 \leq \sqrt{\Delta m_{\text{atm}}^2}$. One can see from Fig. 1 that the results of the CHOOZ experiment imply that $|\langle m \rangle|_3 \lesssim 2.7 \times 10^{-2}$ eV, the results of the Super-Kamiokande experiment imply that $|\langle m \rangle|_3 \lesssim 3.8 \times 10^{-2}$ eV, and the combination of the results of the two experiments drastically lowers the upper bound to

$$|\langle m \rangle|_3 \lesssim 2.5 \times 10^{-3} \text{ eV}. \quad (0.9)$$

Since there is no lower bound for $|U_{e3}|^2$ from experimental data, $|\langle m \rangle|_3$ could be much smaller than the upper bound in Eq. (0.9).

Hence, the largest contribution to $|\langle m \rangle|$ could come from $|\langle m \rangle|_2 \equiv |U_{e2}|^2 m_2$. In the scheme (0.4) $m_2 \simeq \sqrt{\Delta m_{21}^2} = \sqrt{\Delta m_{\text{sun}}^2}$ and, since $|U_{e3}|^2$ is very small, $|U_{e2}|^2 \simeq \frac{1}{2} (1 - \sqrt{1 - \sin^2 2\vartheta_{\text{sun}}})$ [8], where ϑ_{sun} is the two-neutrino mixing angle used in the analysis of solar neutrino data. Therefore, $|\langle m \rangle|_2$ is given by

$$|\langle m \rangle|_2 \simeq \frac{1}{2} (1 - \sqrt{1 - \sin^2 2\vartheta_{\text{sun}}}) \sqrt{\Delta m_{\text{sun}}^2}. \quad (0.10)$$

Solar neutrino data imply bounds for $\sin^2 2\vartheta_{\text{sun}}$ and Δm_{sun}^2 . In particular the large mixing angle MSW solution (LMA) of the solar neutrino problem requires a relatively large Δm_{sun}^2 and a mixing angle ϑ_{sun} close to maximal:

$$1.2 \times 10^{-5} \text{ eV}^2 \lesssim \Delta m_{\text{sun}}^2 \lesssim 3.1 \times 10^{-4} \text{ eV}^2, \quad (0.11)$$

$$0.58 \lesssim \sin^2 2\vartheta_{\text{sun}} \lesssim 1, \quad (0.12)$$

at 99% CL [9]. The corresponding allowed range for $|\langle m \rangle|_2$ as a function of Δm_{sun}^2 is shown in Fig.2 (the shadowed region limited by the solid line). The dashed line in Fig.2 represents the unitarity limit $|\langle m \rangle|_2 \leq \sqrt{\Delta m_{\text{sun}}^2}$. From Fig.2 one can see that the LMA solution of the solar neutrino problem implies that

$$7.4 \times 10^{-4} \text{ eV} \lesssim |\langle m \rangle|_2 \lesssim 6.0 \times 10^{-3} \text{ eV}. \quad (0.13)$$

Assuming the absence of fine-tuned cancellations among the contributions of the three neutrino masses to the effective Majorana mass, if $|U_{e3}|^2$ is very small and $|\langle m \rangle|_3 \ll |\langle m \rangle|_2$, from Eqs.(0.6) and (0.13) we obtain

$$7 \times 10^{-4} \text{ eV} \lesssim |\langle m \rangle| \lesssim 6 \times 10^{-3} \text{ eV}. \quad (0.14)$$

Hence, assuming the absence of an unlikely fine-tuned suppression of $|\langle m \rangle|$, in the case of the LMA solution of the solar neutrino problem we have obtained a *lower bound* of about $7 \times 10^{-4} \text{ eV}$ for the effective Majorana mass in $\beta\beta_{0\nu}$ decay.

Also the small mixing angle MSW (SMA) and the vacuum oscillation (VO) solutions of the solar neutrino problem imply allowed ranges for $|\langle m \rangle|_2$, but their values are much smaller than in the case of the LMA solution. Using the 99% CL allowed regions obtained in [10] from the analysis of the total rates measured in solar neutrino experiments we have

$$5 \times 10^{-7} \text{ eV} \lesssim |\langle m \rangle|_2 \lesssim 10^{-5} \text{ eV} (\text{SMA}), \quad (0.15)$$

$$10^{-6} \text{ eV} \lesssim |\langle m \rangle|_2 \lesssim 2 \times 10^{-5} \text{ eV} (\text{VO}). \quad (0.16)$$

If future $\beta\beta_{0\nu}$ experiments will find $|\langle m \rangle|$ in the range shown in Fig.2 and future long-baseline experiments will obtain a stronger upper bound for $|U_{e3}|^2$, it would mean that $|\langle m \rangle|_2$ gives the largest contribution to the effective Majorana mass, favoring the LMA solution of the solar neutrino problem. On the other hand, if future $\beta\beta_{0\nu}$ experiments will find $|\langle m \rangle|$ in the range shown in Fig.2 and the SMA or VO solutions of the solar neutrino problem will be proved to be correct by future solar neutrino experiments, it would mean that $|\langle m \rangle|_3$ gives the largest contribution to the effective Majorana mass and there is a lower bound for the value of $|U_{e3}|^2$.

Finally, let us consider briefly the two four-neutrino mixing schemes compatible with all neutrino oscillation data [1], including the indications in favor of $\nu_\mu \rightarrow \nu_e$ oscillations found in the short-baseline (SBL) LSND experiment [11]:

$$(A) \underbrace{m_1 < m_2}_{\Delta m_{\text{SBL}}^2} < \underbrace{m_3 < m_4}_{\Delta m_{\text{SBL}}^2}, \quad (0.17)$$

$$(B) \underbrace{m_1 < m_2}_{\Delta m_{\text{SBL}}^2} < \underbrace{m_3 < m_4}_{\Delta m_{\text{SBL}}^2}. \quad (0.18)$$

Since the mixing of ν_e with the two massive neutrinos whose mass-squared difference generates atmospheric neutrino oscillations is very small [1], the contribution of the two “heavy” mass eigenstates ν_3 and ν_4 to the effective Majorana mass (0.5) is large in scheme A and very small in scheme B. Hence, the effective Majorana mass is expected to be relatively large in scheme A and strongly suppressed in scheme B. In particular, in the scheme A the SMA solution of the solar neutrino problem implies a value of $|\langle m \rangle|$ larger than the present upper bound obtained in $\beta\beta_{0\nu}$ decay experiments [12] and is, therefore, disfavored. Furthermore, since the measured abundances of primordial elements produced in Big-Bang Nucleosynthesis is compatible only with the SMA solution of the solar neutrino problem [13], we conclude that the scheme A is disfavored by the present experimental data and *there is only one four-neutrino mixing scheme supported by all data*: scheme B [2].

REFERENCES

- [1] See: S.M. Bilenky, C. Giunti, and W. Grimus, *Prog. Part. Nucl. Phys.* **43**, 1 (1999).
- [2] C. Giunti, [hep-ph/9906275](#) (*Phys. Rev. D*).
- [3] M. Apollonio *et al.* (CHOOZ Coll.), *Phys. Lett. B* **466**, 415 (1999).
- [4] M. Nakahata, these proceedings.
- [5] G.L. Fogli, these proceedings.
- [6] S.M. Bilenky, C. Giunti, C.W. Kim and M. Monteno, *Phys. Rev. D* **57**, 6981 (1998).
- [7] S.M. Bilenky *et al.*, *Phys. Lett. B* **465**, 193 (1999).
- [8] S.M. Bilenky and C. Giunti, *Phys. Lett. B* **444**, 379 (1998).
- [9] Y. Fukuda *et al.*, *Phys. Rev. Lett.* **82**, 1810 (1999).
- [10] J.N. Bahcall, P.I. Krastev and A.Yu. Smirnov, *Phys. Rev. D* **58**, 096016 (1998).
- [11] D.H. White (LSND Coll.), *Nucl. Phys. B (Proc. Suppl.)* **77**, 207 (1999).
- [12] L. Baudis *et al.*, *Phys. Rev. Lett.* **83**, 41 (1999).
- [13] S.M. Bilenky, C. Giunti, W. Grimus and T. Schwetz, *Astropart. Phys.* **11**, 413 (1999).

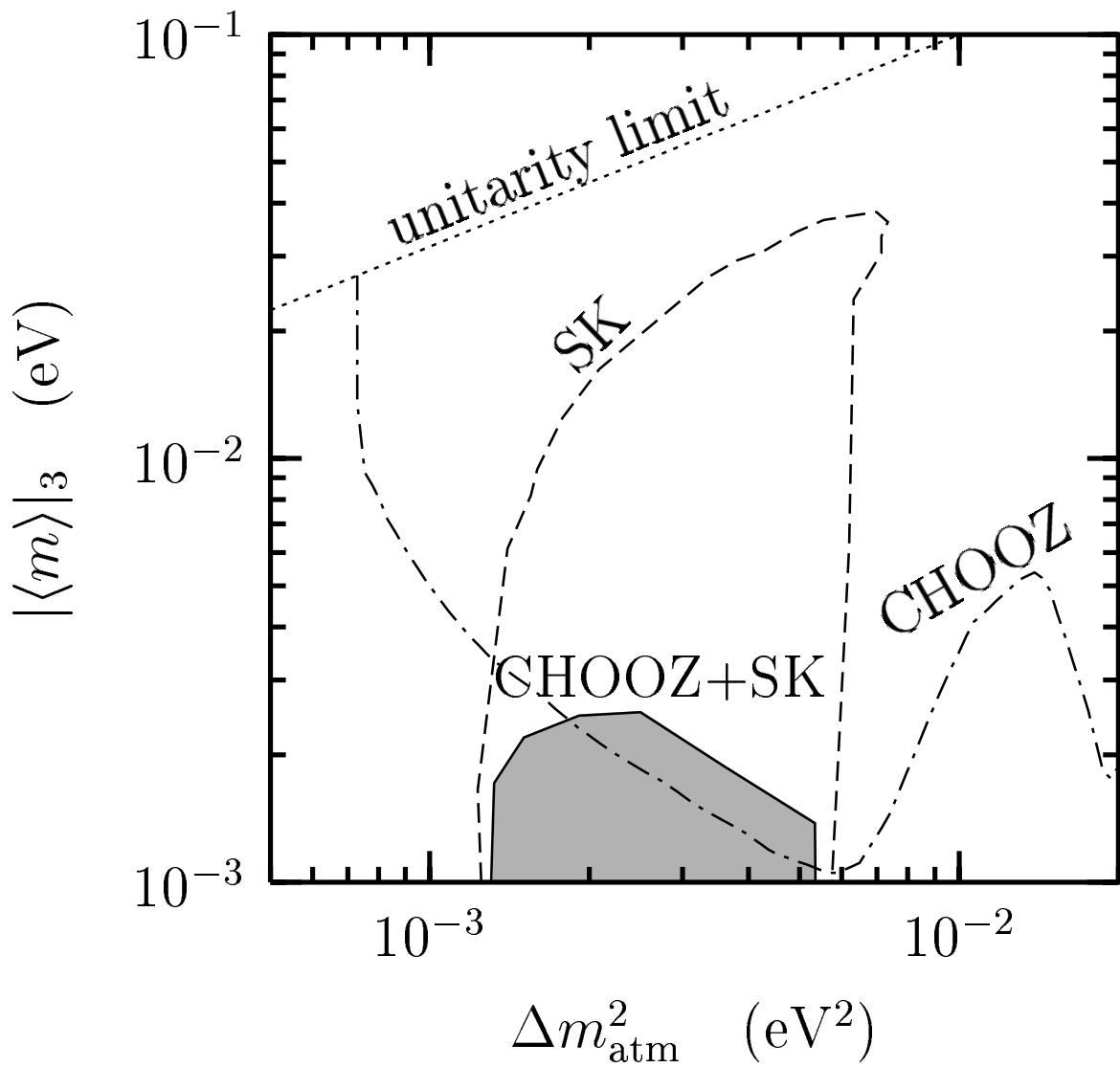


Figure 1

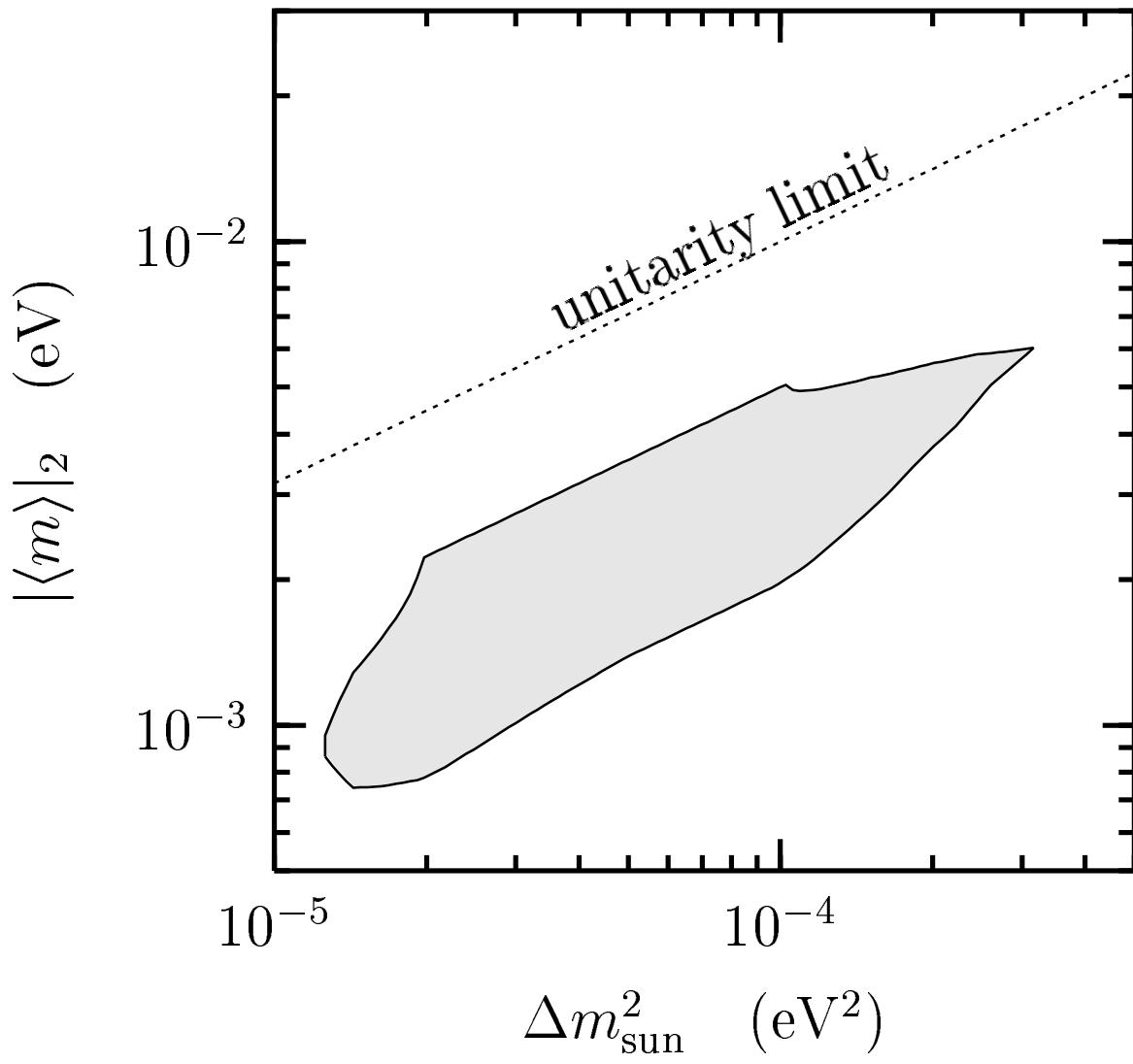


Figure 2